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Synchrotron topography studies of the operation of double-ended Frank–Read partial dislocation sources in 4H-SiC

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ABSTRACT

Synchrotron White Beam X-ray Topography (SWBXT) has been used to image and analyze a distinctive stacking fault pattern observed in 4H-SiC wafers. The pattern often consists of a six-pointed star comprised of multiple layers of rhombus-shaped stacking faults with three different fault vectors of the Shockley type bounded by 30° Shockley partial dislocations. Formation of this stacking fault pattern is associated with a micropipe at its center which can act as nucleation sites for dislocation half-loops belonging to the primary basal ($1/3\langle 11-20\rangle(0001)$) slip system and occasionally the secondary prismatic ($1/3\langle 11-20\rangle\{1-100\}$) slip systems. In this case, the rhombus-shaped Shockley type stacking faults are nucleated on the basal plane by dissociation of $1/3\langle 11-20\rangle$ pure screw dislocations cross-slipped from the prismatic plane and subsequent expansion caused by glide of the leading partial and locking of the trailing partial by interaction with 60° $1/3\langle -2110\rangle$ dislocations on the basal plane. Based on these observations, a formation mechanism involving the operation of a double-ended Frank–Read partial dislocation source has been proposed. In the limit, this glide and cross-slip mechanism leads to 4H to 3C polytype transformation in the vicinity of the micropipe by a mechanism similar to that proposed by Pirouz and Yang (1993) [21].

1. Introduction

The excellent properties of silicon carbide (SiC), a wide bandgap semiconductor, make it highly suited for electronic and optoelectronic devices operating under high temperature, high power, high frequency and/or strong radiation conditions [1]. However, physical vapor transport (PVT) grown commercial SiC wafers contain crystalline imperfections such as micropipes, deformation induced basal plane dislocations (BPDs), planar defects (stacking faults, small angle boundaries), etc. that affect device performance and limit widespread application. Extensive studies have been carried out on the origins and behavior of these defects particularly using a Synchrotron white beam X-ray topography (SWBXT) [2] thereby enabling the development of strategies for eliminating or lowering their densities [3,4]. In the case of stacking faults, three types of stacking faults according to their fault vectors have been reported: the Shockley fault with fault vector of $(a/3)\langle 1-100\rangle$ type [5–7], the Frank fault with fault vector of $(c/2)[0001]$ or $(c/4)[0001]$ [8], and those comprising some kind of combination of the first two [9–13]. Expansion of the Shockley faults into rhombus shapes in the SiC epilayer has been shown to be associated with degradation of power devices [6]. The fault expands though a mechanism whereby the Si-core partials are electrically active, while the C-core partials are not, and the Si-core partials can couple with electron–hole recombination and move. Similarly Shockley faults can expand in response to applied stresses below the brittle-to-ductile transition temperature when C-core becomes sessile and mobile Si-core partial glides [5]. In this study, SWBXT observations of such rhombus-shaped Shockley type stacking faults on the basal plane emanating from micropipes in PVT-grown 4H-SiC wafers have been analyzed and a detailed model has been proposed to explain their nucleation. This model derives from the previously reported interaction between dislocation loops emanating from the micropipes which belong to the prismatic and basal slip systems [16].

2. Experimental

SWBXT images were recorded from PVT-grown 100 mm diameter 4H-SiC wafers in the transmission ($1-100$, -1101 and $11-20$ type reflections) and grazing incidence ($11-28$ type

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reflections) geometries. Grazing-incidence images were recorded from Si-faces of the samples at an X-ray incident angle of 2°. All images were recorded on an Agfa Structurix D3-SC film. The imaging was carried out at the Stony Brook Synchrotron Topography Station, Beamline X-19C, at the National Synchrotron Light Source at Brookhaven National Laboratory. A high resolution transmission electron microscopy (HRTEM) was carried out on the JEOL 2100F at the Center for Functional Nanomaterials (CFN) at Brookhaven National Laboratory.

3. Results

Selected areas of a transmission X-ray topograph recorded from a 4H-SiC substrate are shown in Fig. 1(a) and (b). Various configurations of rhombus-shaped stacking faults can be observed distributed throughout the images. Close examination reveals that the faults are anchored to micropipes in groups forming rosette-like configurations. Each rhombus-shaped fault appears to be confined to one the of six sectors defined by the intersections of two {1 – 100} type planes (with a dihedral angle of 60°) with the micropipe, as shown schematically in Fig. 1(c) where the ⟨11 – 20⟩ traces of these planes on the sample surface are shown. In some cases only one or two of these sectors contain faults, in others up to five of the six are occupied. Fig. 2(a)–(c) shows a series of enlarged {1 – 100} white beam X-ray transmission topographs recorded from region A in Fig. 1(a), showing a rosette comprising of five rhombus-shaped faults (marked S1–S5) surrounding a micropipe, denoted by MP in Fig. 2(a). It can be clearly seen that the edges of each rhombus are along the ⟨11 – 20⟩ directions. The faults are not visible on the {11 – 20} type reflections shown in Fig. 2(d)–(f) although dislocation lines apparently forming the outlines of the faults are selectively visible. For example, the dislocations forming the outlines of faults S1, S3 and S4 are visible in Fig. 2(d), those outlining S1, S2, S4 and S5 are visible in Fig. 2(e) while those outlining S2, S3 and S5 are visible in Fig. 2 (f). Application of the **g**•**R** criterion (where **g** is the reflection vector and **R** is the stacking fault vector) to Fig. 2(a)–(f) demonstrates that all five stacking faults are Shockley type with fault vectors of type 1/3⟨1 – 100⟩ bounded by 1/3⟨1 – 100⟩ Shockley partials where both the fault and partial Burgers vectors point along the long diagonals of the rhombuses so that each of the partial loop segments is of 30° character. The variations in the density of fault contrast observed in Fig. 2(a)–(c) suggest that faults S1–S5 comprise of several faults superimposed. Clearer evidence for such multiple fault configurations can be found in Fig. 3(a)–(f) which show enlargements of the {1 – 100} and {11 – 20} images of one of the faults from region B indicated in Fig. 1(b) located in an area with a lower background dislocation density. The superimposition of a number of Shockley faults on different basal planes is discerned from the fact that the outer perimeters of the faults do not precisely superimpose, with fault sizes decreasing towards the micropipe, with the smaller faults closer to the micropipe appearing darker due to contrast overlap. Further evidence for this can be found in the enlargements shown in Fig. 3(d) and (f) (g={11 – 20}) where the Shockley partials delineating the perimeters of the faults are in contrast and have the appearance of approximately concentric loops of size increasing away from the vicinity of the micropipe which have been sequentially emitted from there. The fact that these partials are absent in Fig. 2(e) confirms through the application of the **g**•**b** criterion that the Burgers vector of the loops is 1/3[10 – 10], i.e., they are Shockley partial loops which bind Shockley faults with the same fault vector. In addition, in the same region various sets of approximately concentric basal plane half-loops can be seen emanating from the micropipe, for example as indicated by B1 and B2 in Fig. 3(d)–(f).

4. Discussion

Single rhombus-shaped Shockley faults have been previously observed to form during the forward bias of p–i–n diodes wherein the dissociation of basal plane dislocations (BPDs) is driven by electron–hole recombination which preferentially activates the

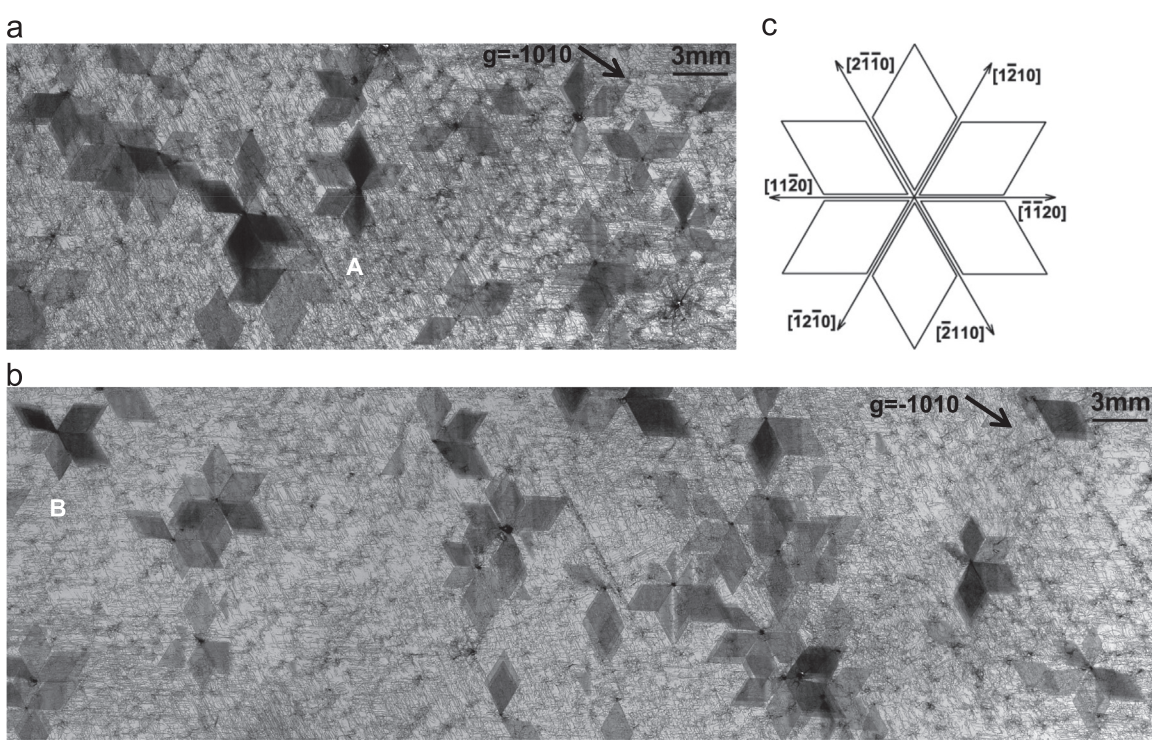

Fig. 1. (a) and (b) X-ray transmission topographs from a 4H-SiC substrate showing various configurations of rhombus-shaped stacking faults anchored to micropipes in groups forming rosette-like configurations; (c) schematic showing ⟨11 – 20⟩ traces of the intersecting {1 – 100} type planes around a micropipe.

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